Should the Federal Government Invest in an Accelerated Commercial Demonstration of High Burnup Light Water Reactor Fuel to Ease the Burden of Spent Fuel Disposition?

Herbert Feinroth
Chief Executive Officer, Ceramic Tubular Products LLC
hfeinroth@gamma-eng.com

Prepared for the President's Blue Ribbon Commission on America's Nuclear Future

The charter of the Blue Ribbon Commission is to recommend a path forward for dealing with the Nation's nuclear spent fuel. Today, the 104 commercial nuclear plants are producing more than 2000 tons of additional spent fuel each year. When added to the 60,000 tons of spent fuel already generated, this will yield a total of 110,600 tons just from existing plants, assuming that 90% of these plants are relicensed for a 60 year lifetime. If we assume that retiring plants are replaced with new plants, keeping the base at the current 104 plants, there will be 140,000 tons of spent fuel by 2050.

A new fuel cladding technology has emerged in the last decade that has the potential to increase the amount of energy extracted from each kilogram of commercial nuclear fuel by 50 to 100% and thereby substantially reduce the amount of fuel required for future energy production and available for ultimate disposition. We believe that an accelerated program to develop and commercialize this new fuel cladding technology would be in the National Interest, regardless of the path forward for ultimate disposition of spent fuel. We have prepared this white paper to inform the Commission of this opportunity and request its support.

The technology involves the replacement of the current zirconium alloy cladding used to contain nuclear fuel with a new multi-layered ceramic cladding. The new clad technology has been under intensive development for the last ten years. In addition to its capability to achieve very high burnup, tests in US research reactors have shown this new cladding will increase the safety of nuclear fuel, and thereby enhance the ability of current nuclear plants to continue safe operation beyond the current licensing limit of 60 years. Details of this technology, including results of tests, remaining development challenges, and a proposed path forward for commercial development, are presented in the attachment to this white paper.

With a focused program jointly funded and executed by industry and our National Laboratories, we believe it is entirely possible to complete the initial phase of development, and insert lead test rods into commercial reactors within five years. We have proposed such a program to the Congress and the DOE. If this first phase is successful, it would be followed by licensing and commercial demonstration to be completed the early 2020's. Commercial deployment in current US nuclear plants would begin by 2025. Thereafter, deployment in the current nuclear fleet would reduce the rate of spent fuel production by substantial amounts. For example, assuming that the size of the current fleet remains the same as today through 2050, we estimate that the amount of spent fuel requiring Government disposition by 2050 would be reduced from the current expectation of 140,000 tons, to between 115,000 and 121,000 tons with this higher burnup fuel. This in turn would reduce the cost for shipping and disposing of spent fuel in an underground repository by $2.7 to $3.6 billion. This estimate is based on the latest published DOE Office of Civilian Radioactive Waste Management unit cost estimates, corrected for the increased heat generation rate of the higher burnup fuel which would result in higher unit costs. Savings for other disposal or reprocessing options are likely to be greater than this amount.

There is an additional National benefit to deployment of this new ceramic clad fuel. Tests have demonstrated that it can survive severe accidents because of its very high temperature capability, as compared to zirconium alloys. Although the current plants have been safely operated and well regulated, and have extremely low accident risk, they will be getting older as time goes on, and as they get older, the components and structures will surely deteriorate, despite the best maintenance practices. It is uncertain if a case can be made for relicensing them beyond sixty years. DOE and industry have recently initiated a materials based research program to study this question. The new ceramic clad fuel is much more resistant to damage during severe accidents as compared to the current metal clad fuel. It does not release combustible gases during loss of coolant accidents, does not release large amounts of thermal energy during such accidents when quenched with water, and can retain its strength and robustness to very high temperatures, thus maintaining core coolability after severe accidents, a key licensing requirement. This additional passive safety feature could well offset the degradation in plant systems and components beyond their 60 year lifetime, and thereby enable the relicensing of these plants to 80 years or more, an extremely valuable contribution to the Nation's energy future.

In addition to National benefits, application of this technology could be of substantial economic benefit to nuclear plant owners, and their rate payers, particularly in view of its potential to allow for additional power upratings (of 20% or more), for existing plants. However, industry investment in an accelerated development program has been limited because, as in any new nuclear technology, there is significant risk of regulatory delays, and in technology setbacks. Although the DOE has begun to provide limited funds for testing in research reactors at Oak Ridge and MIT, the current policy at DOE and its laboratories is focused on materials research, and development of new analytical methods to enable high burnup fuel. In DOE's July, 2010 testimony to this Commission they present a "notional" schedule for researching advance fuels technology, including high burnup fuel, leading to commercial introduction in the mid 2040's. We believe that with the encouragement of this Commission, it is possible to initiate a joint industry – Government cost shared program focused on near term commercial demonstration, supported by ongoing laboratory materials research, leading to commercial introduction within fifteen years or sooner.

This past summer, the Senate Appropriations Committee reported out a bill for funding the DOE in FY 2011 which stated in part:

Fuel Cycle Research and Development.-The Committee recommends $191,000,000 for Fuel Cycle Research and Development. The Committee recommends $40,000,000 for the Advanced Fuels program, including $7,000,000 for the Department to issue a competitive solicitation requesting industry teams (fuel suppliers, utilities and advanced ceramic developers) for cost shared proposals to develop and test advanced LWR fuel with ceramic cladding, with the capability of very high burn up and with the objective of achieving readiness for Lead Test Rod *operation in commercial reactors within 5 years. This should be awarded on a 50-50 cost-share basis.*

Although this new program has yet to become law, and has not yet been endorsed by the Executive Branch, we believe it is the only path forward that has a good chance of succeeding. If endorsed by the Commission, and enthusiastically implemented by the Executive Branch, we believe the Government investment would be matched by similar investment from nuclear plant owners and their suppliers, leading to a successful, industry led, Government supported commercialization program.

We have been asked for an estimate of the total cost of the commercialization program. There is great uncertainty because we are not sure which of several possible approaches will be required to overcome the remaining technical and regulatory obstacles. Our guess is that the first phase, inserting lead test rods into commercial reactors within five years, as suggested in the Senate language, would require funds of about $100 to $200 million, depending on whether a single team, or multiple teams, are selected by DOE for this program. If successful, this first phase would be followed by a second phase, involving tests under severe accident conditions to prove the material's passive safety features, and substantial analyses to provide the basis for licensing, as well as the fabrication and licensing of full sized lead fuel assemblies. We would not recommend initiating the second phase until technical obstacles are resolved, and results of the first phase are clearly favorable. Because the new fuel technology may also improve the efficiency and economics of the nuclear plants themselves (e.g. power uprating), it is possible that the plant owners would invest a large share in this final commercialization and licensing phase.

We believe it would be directly in line with the Commission's charter to review this technology and evaluate its potential, and based on that review, endorse it for execution as soon as possible. We recommend that you do so. The attachment outlines some of the details of the technology, and the results of testing we have already performed, and provides a more detailed explanation of why we believe it will support high burnup fuel, whereas zirconium based cladding will not. We and our colleagues in the ceramic industry are available at your convenience to answer any questions you may have.

Sincerely,

Herbert Feinroth

Herbert Feinroth,
Chief Executive Officer
Ceramic Tubular Products LLC
15815 Crabbs Branch Way
Rockville, Maryland 20855
301-840-8415

Commercial Demonstration of Ceramic Clad High Burnup, Passively Safe, Light Water Reactor Fuel

1. What are the reasons why the current zirconium alloy clad cannot achieve high fuel burnup?

Since the first commercial water reactor began operating in the U.S. in 1957, zirconium alloys have been used as the primary containment barrier for nuclear fuel. Zirconium has very low neutron absorption, and was originally developed for use in military reactors in the 1950's. Figure 1 shows the first commercial use of zirconium alloy in tubular form at the Shippingport Atomic Power Station, the prototype commercial water reactor developed at Bettis Laboratory under the direction of Admiral Rickover and the Naval Reactors Branch of the Atomic Energy Commission. Today, it has been adopted for almost all nuclear plants in the US and overseas.

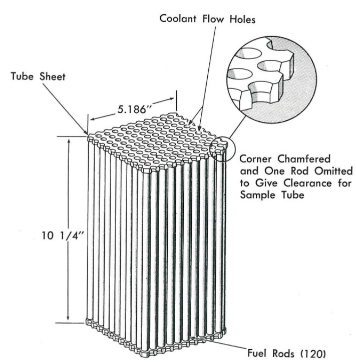


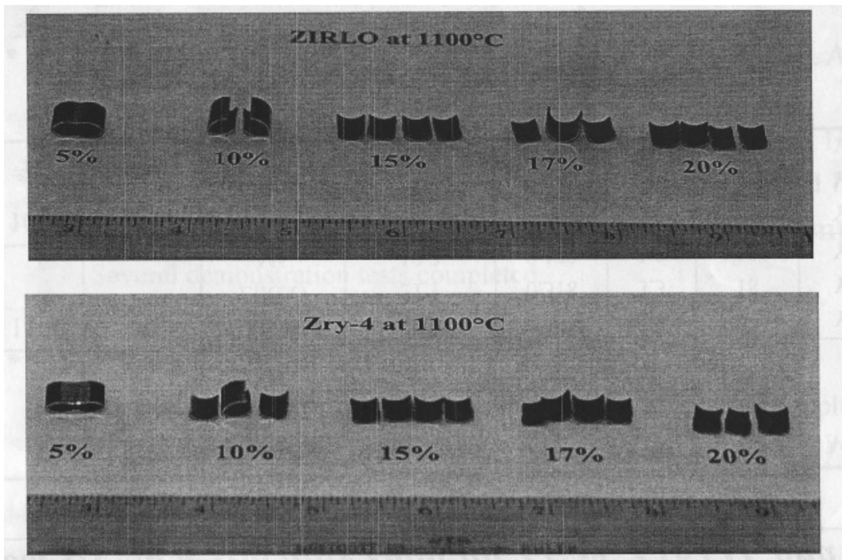
Fig. 4–15. Blanket bundle.

Shippingport Atomic Power Plant Zircaloy Clad Blanket Fuel Bundle – December, 1957

The performance of this zirconium alloy cladding has steadily improved to the point where most plants operate with no fuel failures through end-of-life, even as burnups approach currently licensed limits (62 mwd/kg peak rod; about 40 to 50 mwd/kg batch average) and as operating environments continue to change as plants age. Through the early 1980's achievable fuel burnup was limited by the cladding to about 20 to 30 mwd/kg batch average; however, under the umbrella of a joint industry – DOE program initiated in 1980, the zirconium alloy clad fuel rods underwent significant improvements leading to current peak rod burnup limits of 62 mwd/kg equivalent to a batch average burnup of about 45 mwd/kg. Further improvements in performance and reliability are still being pursued worldwide, and many expect that zirconium alloy cladding can be reliably used to burnups of 75 mwd/kg peak or 60 mwd/kg batch average.

The reason that zirconium alloy cladding cannot support much higher fuel burnups, or higher power ratings, has to do with their chemical oxidation, and loss of strength at temperatures above the 300 ^{o}C operating temperatures of water reactors.

The zirconium alloy clad gradually oxidizes and becomes brittle after several years in reactor coolant, such that it is subject to failure during a loss of coolant accident such as occurred at the Three Mile Island in 1979. The figure below shows the behavior of modern zirconium alloys under a C-ring compressive stress test on small sections of cladding exposed to hot water and steam for various times and at high temperature. As shown on this illustration, the rings of zirconium alloy remain ductile if the oxidation is limited to 5%, but become brittle with increased oxidation at 10% and above. For this reason, current Nuclear Regulatory Commission regulations limit the total oxidation levels that can be allowed before and during a loss of coolant accident to no more than 17%.

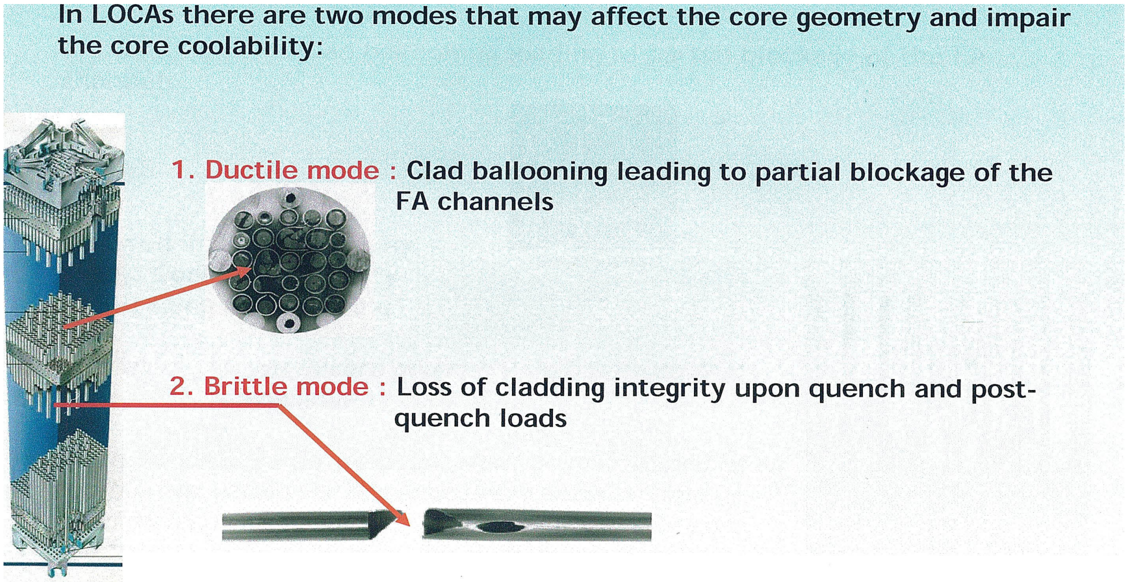


Zirconium Alloy Clad Behavior Under Mechanical Stress After Oxidation

These limits contribute to the allowable fuel durability of about five years in a reactor, and a peak burnup in each individual fuel rod of 62 mwd/kg as mentioned above. Regulatory limits in other countries are sometimes higher or lower, and some improvements are being made to the zirconium alloy that might increase their capability by another 10 or 20%. Till recently, there has not been any alternative to the zirconium alloy cladding. Consequently, the industry, and the DOE spent fuel program, have more or less accepted this 62 mwd/kg peak, or 45 mwd/kg average, burnup technical limitation.

A second limitation of zircaloy cladding that impacts its behavior during an accident, and also limits the amount of power density that can be achieved in a zircaloy clad core, is that it loses almost all of its strength above about 500 ^{o}C. This is illustrated in the figure shown in section 2 below, which compares the zirconium alloy high temperature behavior with that of silicon carbide composites. When temperatures of zircaloy cladding exceeded 700 ^{o}C during the Three Mile Island during the accident in 1979, the internal fission gas pressure within each fuel rod caused the fuel cladding to balloon, and block the flow of emergency cooling which was pumped into the reactor vessel after the accident. This caused the core to overheat and eventually melt.

And a third limitation of zircaloy is that it reacts exothermically with water at elevated temperatures and thus contributes directly to the severity of a loss of coolant accident. During this reaction it releases hydrogen gas which further exacerbates the accident. The figure below is from a test program that illustrates this ballooning, and brittle behavior of zircaloy clad during accidents.



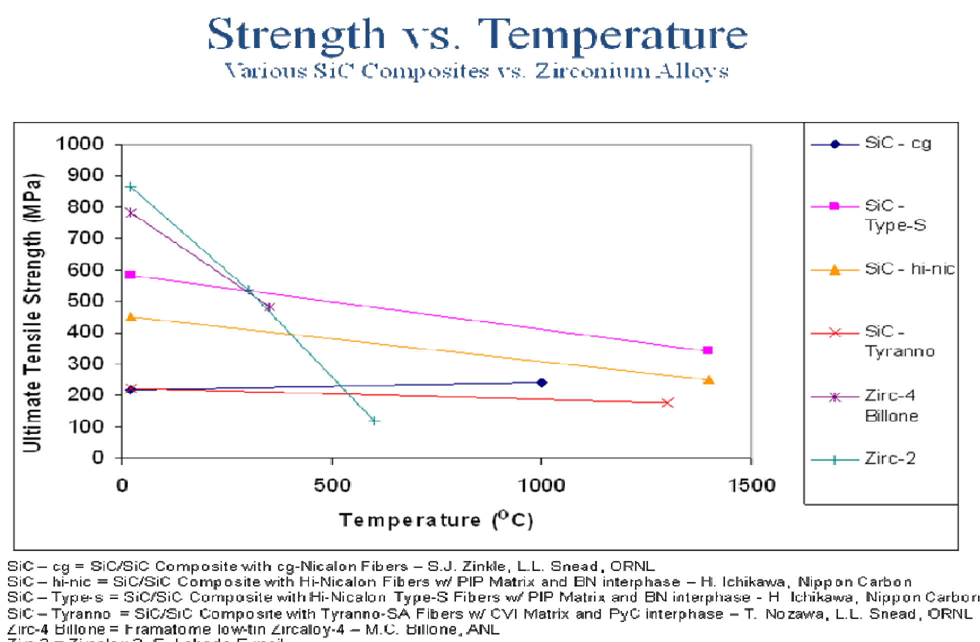
Failure Modes of Zircaloy Clad Fuel During a LOCA Accident

2. How can one use a "brittle" ceramic in such a harsh environment as a Light Water Reactor core? Won't the cladding shatter during abnormal events and accidents?

While the usual type of monolithic ceramic used in everyday life is indeed brittle, and not adaptable for nuclear use, this is not the case for the "Triplex Silicon Carbide Fuel Cladding" that has been developed in recent years. This clad concept involves the use of a composite material in its central layer that is not brittle, and instead behaves like a metal when subject to mechanical loads. That is, it stretches under load without fracture, and when it does exceed allowable stress, fails in a graceful failure mode very similar to the failure behavior of ductile metallic cladding.

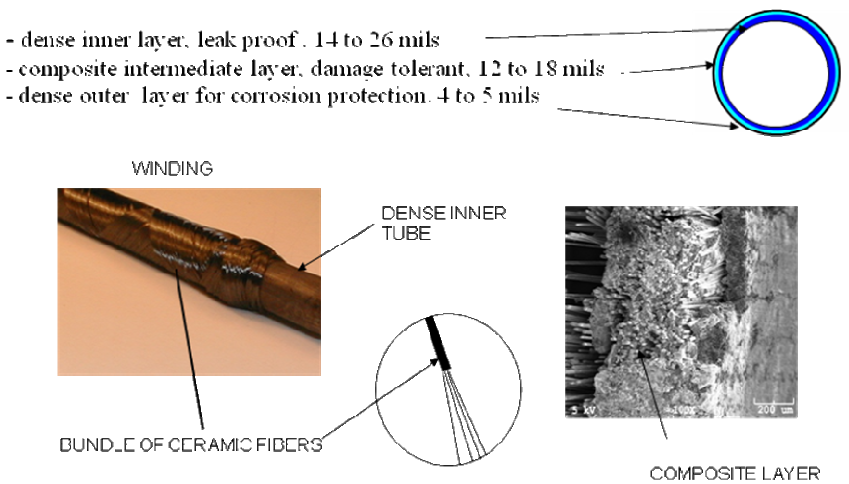
The idea of replacing metal fuel cladding with a ceramic composite began to emerge after extensive study of the core that essentially melted in the accident at Three Mile Island Unit 2 (TMI-2) in 1979. Early investigations, sponsored by the NRC and by DOE, studied a ceramic composite made from alumina fibers and an alumina matrix, known as a continuous fiber ceramic composite (CFCC). Under the accident conditions at TMI-2, such a cladding material would not have ballooned and blocked flow, there would have been little heat generated by the exothermic cladding reaction, the fuel would not have melted and been dispersed. In fact, if a ceramic cladding had been in use at TMI-2 before the accident, it may have been possible to replace the damaged core and resume operation of the plant, thus saving several billions of dollars (the cleanup alone was around $2 billion). However, our early investigations concluded that alumina composites were not acceptable for two reasons – the composite was permeable to fission gases, and the alumina lost much of its strength during irradiation.

We then turned our attention to a multilayered ceramic system that would embody the hermeticity needed to retain fission gas, and the ductile behavior needed for robust in-pile service. The inner layer would be a high density monolith to hold fission gases, and the outer layer would be a composite with the required strength and graceful failure mode. We also switched from alumina to silicon carbide, based on many years of Government sponsored fusion research that demonstrated this ceramic would retain its strength under irradiation. As shown in the figure below, silicon carbide composites retain their strength at temperatures at 1500 °C and higher, as compared with zircaloy which loses most of its strength above 500 °C. The high strength at high temperature assures survival of the triplex SiC clad with minimum damage (fission gas release only) during LOCA events. The material is also expected to be resistant to failure during departure from nucleate boiling (DNB) transients, thus allowing an increase in power density, and power output. And because silicon carbide is very hard, it is expected to be resistant to operational fuel failures sometimes caused in zirconium alloy fuel rods by grid fretting and debris.



High Temperature Strength of Various Silicon Carbide Composites vs Zirconium Alloys

In 2001, a second DOE research grant was awarded to study the multilayer silicon carbide concept. The key innovation introduced by this effort was to improve the strength of the multilayered tube with a unique fiber winding architecture and by pre-tensioning the fibers. Such a tube could withstand very high internal fission gas pressure prior to breaching the inner monolith tube. Several different fiber architectures were examined, leading to a unique fiber winding machine to control the fiber architecture and tension. In addition, we added a third dense outer layer of monolithic SiC to enhance corrosion resistance. The design, called "triplex ceramic cladding," is shown in the figure below.



The Three Layer Concept of CTP's "Triplex SiC Cladding"

This design allows for independent optimization of the properties of the inner monolith for fission gas retention, the fiber-reinforced matrix for overall mechanical performance, and the outer monolith for corrosion resistance. For example, on one particular triplex clad design, tests at Oak Ridge and MIT have demonstrated that the SiC triplex tube can withstand pressures of over 5000 psi, as compared to the maximum internal pressure of 2000 psi allowed in a zirconium alloy tube. This is an important capability that allows high burnup even with increased fission gas release.

Furthermore, during the mechanical tests at Oak Ridge, the triplex clad tube continued to retain its basic shape even after the inner monolith developed a crack resulting from high internal radial loads. Total strain on the cladding during internal loading exceeded 8% radial strain, while the composite layer retained its basic cylindrical shape, without gross fracture or ballooning.

3. How can one increase the fuel burnup, even with a more durable ceramic clad, without increasing the U^{235} enrichment beyond today's license limits, and thereby allow increased energy to be extracted from each fuel assembly?

Use of durable ceramic clad is a necessary, but not sufficient, prerequisite to achieve high burnup LWR fuel. A second important factor limiting today's LWR fuel burnup to about 45 – 50 mwd/kg average, is a limit on the amount of $uranium^{235}$ enrichment in the uranium fuel. Today, most U.S. commercial fuel factory equipment and shipping casks are designed to be criticality safe only at U^{235} enrichment levels up to 5%. Higher enrichments are required for higher burnups, and some of the equipment, and processing procedures, would have to be changed to allow these higher enrichment levels. This is not a technology issue, as some US industrial facilities have been producing much higher enrichments for use in Naval Fuel for many decades. Rather, it is an infrastructure issue, a question of investment in upgrading the equipment and shipping casks, and relicensing them for the higher U^{235} loading. Industry has been reluctant to consider such investments, because up till now, the cladding limit would not permit them to take advantage of the higher fuel burnup allowed by the higher enrichment. With the introduction of an advanced ceramic cladding, that would no longer be a hindrance to such investment.

4. What are the safety and regulatory implications of switching from the proven zircaloy clad to a new ceramic cladding, and what will be required to achieve regulatory approval?

The Nuclear Regulatory Commission has published an Advanced Notice of Proposed Rulemaking (RIN 3150-AH42) indicating its intent to revise the current NRC rules on Emergency Core Cooling Systems as it effects fuel clad integrity during accidents. NRC's intent is to make this rule more "performance" based, rather than "prescriptive" based.

NRC plans to expand the rule to apply to all cladding material, and not restrict it to zirconium alloy or steel cladding, as it has in the past. The rule will require that licensees and their fuel suppliers provide evidence that each new clad composition satisfies the three major safety criteria regarding behavior during a design basis LOCA. The emergency core cooling system (ECCS) must be designed so that its calculated cooling performance following a postulated LOCA satisfies the following requirements:

> Coolable geometry. Calculated changes in core geometry shall be such that the core remains amenable to cooling;
>
> Maximum hydrogen (combustible gas) generation. The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount …..
>
> Long -term cooling. After any calculated successful operation of the ECCS, the calculated core temperature shall be maintained at an acceptable low value …..

Based on the tests we have performed to date on silicon carbide materials, there is little question that Emergency Core Cooling Systems in operation today will be more than sufficient to assure that the silicon carbide cladding will meet these three conditions. In fact, because of the properties (absence of exothermic reaction , avoidance of combustible gases, avoidance of ballooning , and very high temperature durability) we believe that future Emergency Core Cooling Systems can be simplified, and also that the heat ratings in current reactors can be substantially increased while still meeting these criteria. One of the key tasks in the remaining test and development program will be to provide the experimental evidence to support this prediction using actual fuel and cladding materials in a reactor test environment.

5. Feasibility of high burnup ceramic clad fuel: research and testing to date, and remaining technical obstacles.

Since 2001, we have tested seven different versions of Silicon Carbide fuel cladding, with different varieties of monolith tubes, fiber compositions, matrix deposition methods, and environmental barrier coatings. Testing has been done in a prototype PWR coolant environment in the MIT research reactor, with some optimized clad specimens achieving over 20 full power months of exposure so far, and with exposure ongoing as of this date. Room temperature mechanical tests have been performed at the Oak Ridge National Laboratory, and at Ceramic Tubular Products facilities in Lynchburg, VA. In addition to the experimental work, there has been significant modeling and analysis to predict the performance of the cladding and contained fuel in a commercial environment, including work sponsored by the Electric Power Research Institute to determine how best to incorporate the triplex cladding into a typical PWR core design and fuel management cycle. And recently, a test has begun in the Oak Ridge High Flux Isotope Reactor (HFIR) to operate commercially fabricated uranium fuel pellets with silicon carbide triplex cladding under typical average heat ratings found in today's commercial reactors. The purpose of this test is to evaluate any possible pellet clad interaction that might occur in the fuel rod during operation. This test is supported with DOE funds allocated from DOE's LWR Sustainability Program, and is planned to continue for several more years.

Some positive output from this development and testing to date include:

- The recision rate of the outer barrier layer during the initial 20 months of exposure in the MIT reactor, extrapolates to a life of 6 to 10 years, enough to support the high burnup objectives of the proposed technology demonstration program.
- The combination of strong monolith and tightly wound and infiltrated central composite layer will support very high internal gas pressures, 2 to 3 times the level that can be achieved with zircaloy clad fuel. Zircaloy cladding creeps under pressure and therefore must operate with a fission gas pressure below plant operating pressure of 2000 psi. Silicon Carbide clad does not creep and therefore can sustain much higher fission gas release which occurs with high burnup.
- Exposure to the high radiation environment in the MIT reactor does not significantly reduce the strength of the cladding material.
- When a triplex clad is mechanically loaded to failure, either due to pellet swelling or high gas pressure, the composite layer maintains its shape even after the inner monolith fails. This would assure, under severe accident conditions, that the solid fuel would be retained and not released to the coolant, even after the fission gas is released due to the initial failure.

Some tests led to results that require further optimization of the product before it can be demonstrated in a commercial environment. This optimization would be the main focus of the proposed five year development program leading to lead test rod insertion in commercial reactors. Some of the more challenging development work remaining includes the following:

- Developing a bond agent to seal the joint between the fuel rod end cap and the clad tube. During early 2010, a number of different bond agents were irradiated in the MIT research reactor and five of six test specimens failed the test. Alternative bond agents are being formulated and must be tested as part of the proposed program.
- Fabrication and testing of much longer fuel tubes than the short length tubes already fabricated and testing. Existing equipment has been identified to fabricate six foot long tubes which may be sufficient for the initial lead test rod demonstration. Ultimately, new equipment must be designed and developed to fabricate the 14 foot long tubes required for full commercial deployment.
- Modifying the fiber architecture of the composite layer to increase the impact resistance of the loaded fuel rod during fabrication and shipping. An incident that occurred during the initial fabrication of the HFIR test specimens revealed that the current design has insufficient impact resistance. Further optimization of the fiber architecture, or the fiber to matrix interface design, or both, is required to provide adequate impact resistance.
- Integral testing with typical heat ratings, and flowing PWR coolant, is required to assure acceptable performance, prior to inserting lead test rods into commercial reactors. This cannot be done in either the MIT research reactor, or the HFIR reactor, and requires either a new coolant loop in the ATR reactor, or use of other international test reactors such as Halden, NRU, MIR or Hanaro.
- Further integration of the fuel pellet design with the triplex cladding design is required. Fuel performance analyses by both MIT and EPRI indicate that a central void in the fuel pellet may be required to accommodate high heat ratings without exceeding regulatory limits for the pellet central temperature. Although fuels with central void have been licensed and operated in commercial reactors, the specific design that will ensure acceptable performance for long life, and with minimum increase in enrichment, must be developed for use in the proposed lead test rod program.

The proposed five year development program, jointly funded by DOE and the industry, and awarded on a competitive basis, will be designed to address and resolve these challenges. If successful, and after initial successful operation of the lead test rods in a commercial nuclear plant environment, we believe there will be sufficient confidence in the potential for high burnup fuel to warrant proceeding with the final phase of lead test assemblies, transient and accident testing, licensing by the NRC, and manufacturing scale-up.

6. How will a transition to triplex silicon carbide clad and high burnup fuel affect the safety and cost of spent fuel storage, transportation, and disposition?

New and spent fuel storage and transport equipment will have to be evaluated and possibly changed, to reflect the new clad material, the higher enrichment in new fuel, and the higher burnup in spent fuel.

Because the silicon carbide cladding is more durable than current zircaloy cladding, especially after many years of exposure, we believe that the safety of storage, transport and disposal will be greater, and will justify the required NRC license amendments. Corrosion data under storage and shipping conditions will be needed to support the licensing case, and this will be one task under the proposed accelerated development program.

With regard to the higher enrichment and higher burnup features of the advanced fuel system, account must be taken of the higher fissile loading, and the higher heat generation rate in spent fuel. This will require greater spacing during storage, shipment and disposal, which will increase the cost per kilogram of fuel. But there will be a large reduction in the number of kilograms of fuel required per unit of energy produced, more than offsetting this spacing effect. In the cost evaluation reported in section 7 below, we have included a 20% increase in the cost of transportation and disposal of each spent fuel assembly to allow for this spacing effect.

7. What are the economic benefits to DOE considering its legal obligation to transport and disposition all commercial spent fuel?

Our evaluation shows considerable savings to DOE (actually to the Waste Fund collected by DOE from nuclear plant owners contributions) resulting from commercial deployment of high burnup fuel. We examined the case wherein the Nation continued to generate electricity from nuclear power through 2050 at the same level as currently being produced by the 104 plants. Essentially, this assumes that each plant that is retired after a 60 year operating period is replace by a new plant of similar capacity, without any overall growth in US nuclear generating capacity. This is probably a conservative assumption, as it is likely there will be some additional growth in nuclear capacity over the next 40 years from construction of new plants.

As a base case, we assumed no increase in average burnup over the current levels of about 45 mwd/kg. We then looked at the reduction in quantity and cost, assuming high burnup fuel at 80 mwd/kg beginning in 2025, and a second case assuming 100 mwd/kg beginning in 2025. For costing purposes, we used the latest cost report prepared by the DOE, DOE/RW-0591, "Analysis of Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007", issued in July, 2008. We addressed only the incremental cost of shipment and disposal, and not the disposal facility capital costs. We also corrected for the increased heat generation rate of the spent fuel, adding 20% to the unit costs for shipping and disposal. Results of this simplified analysis are:

The base case, continuing at current burnup levels through 2050, leads to a total accumulated spent fuel burden of 140,000 tons by 2050.

The modest high burnup case, 80 mwd/kg beginning in 2025, leads to a total spent fuel burden of 121,259 tons by 2050, a reduction of 18,750 tons compared to the base case. Cost savings for shipping and geologic disposal, and accounting for the 20% decay heat penalty, are estimated at **$2.7 billion**.

The target high burnup case, 100 mwd/kg beginning in 2025, leads to a total spent fuel burden of 115,000 tons by 2050, a reduction of 25,000 tons compared to the base case. Cost savings for shipping and geologic disposal, and accounting for the 20% decay heat penalty, are estimated at **$3.6 billion**.

8. What are the economic implications of high burnup fuel to nuclear plant owners and their ratepayers?

Nuclear plant owners would face an initial incremental cost associated with the transition to advanced ceramic clad, high burnup fuel. Front loaded costs would include licensing and operation of lead test assemblies, design and licensing of full core reloads with advanced cladding, some possible changes to new fuel storage equipment, and spent fuel storage (wet and dry) equipment for the higher enriched and higher burnup fuel, changes to handling procedures, and NRC license amendments to allow for these changes. In the out years, beyond 2025, we believe these front loaded costs would be more than offset by an additional 20% power up-rate capability, and by longer cycle lengths, allowing for increased capacity factors. Perhaps the largest economic benefit would be the ability to relicense existing plants beyond the current limit of 60 years, something that will be difficult to achieve without the added accident risk reduction that will be achieved from the use of passively safe fuel.

9. Can the Silicon Carbide Triplex Cladding be used in advanced fuel cycles, for example with thoria plutonia fuel, and thereby enable the modified open fuel cycle suggested by some as a solution to the Nations spent fuel problem?

Ceramic Tubular Products has been studying this question for the last four months under a new Small Business Grant awarded by the DOE in August, 2010. So far the answer looks positive, but more work needs to be done. The specific fuel cycle option we have been studying is a commercial light water reactor fuel design that couples our durable triplex SiC cladding, with a thoria-plutonia fuel system under development by Thor Energy in Norway. From a fuel cycle perspective, this fuel system offers the prospects for destruction of a large percentage of the actinides, including plutonium and americium, in a single additional cycle in current LWRs. Using thoria instead of depleted uranium as the diluent for a fissile plutonia MOX type fuel system, makes enormous sense. Instead of producing more plutonium during operation, as is the case with traditional MOX, this system destroys most of the plutonium in a single fuel cycle. This fuel system still requires that the initial spent fuel now accumulating at the Nation's nuclear plant sites, be subjected to a single pass through a reprocessing facility, with fission product waste being isolated and immobilized, the 95% uranium content being stored and disposed of as low level waste, and the actinides, including plutonium, being mixed with thorium, incorporated into standard design LWR fuel assemblies, and cycled in one pass through existing LWRs. In principle, this system can operate using traditional zircaloy cladding. However, the benefits are limited because zircaloy clad will not permit a burnup much above 50 mwd/kg average burnup, allowing a smaller portion of the actinides and plutonium to be destroyed. Our initial calculations show that with silicon carbide cladding, it is possible to achieve 100 mwd/kg over a period of 6 years (3 cycles) and destroy over 60% of the recycled plutonium. This is not as good as the multiple-cycle fast reactor concept, but something that can be achieved with current commercial water reactors. Our main focus today is to apply the SiC cladding to existing LWR uranium oxide fuel. However, this study opens the door for a second generation of ceramic clad fuel that could further reduce the long term burden of disposition of nuclear spent fuel, making partial use of the remaining energy content in that spent fuel.